Planck constraints on scalar-tensor cosmology and the variation of the gravitational constant

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Ooba et al. (2016)
Introduction

Modified gravity

- Extended theory
- Constraint
  - CMB (cosmic microwave background)

- scalar-tensor
- f(R)
- Galileon
- Horndeski
- GLPV ...

The gravitational theory of our universe
Scalar-tensor theory (harmonic attractor model)

Action:

\[
S = \frac{1}{16\pi G_0} \int d^4x \sqrt{-g} \left[ \phi R - \frac{\omega(\phi)}{\phi} (\nabla \phi)^2 \right] + S_m
\]

Coupling parameter:

\[
2\omega(\phi) + 3 = \left\{ \alpha_0^2 - \beta \ln(\phi/\phi_0) \right\}^{-1}
\]

- 0 : Today’s scalar field value
- \(\alpha_0, \beta\) : Today’s potential gradient and curvature

\[\alpha_0 = \beta = 0 \rightarrow \text{GR is recovered}\]

Damour and Nordtvedt (1993)
Nagata et al. (2002)
Background equations

Energy conservation:
\[ \rho' + 3H(\rho + p) = 0 \]

Friedmann eq:
\[ H^2 = \frac{8\pi G_0}{3\phi} \rho a^2 - H \frac{\phi'}{\phi} + \frac{\omega}{6} \left( \frac{\phi'}{\phi} \right)^2 \]

Scalar field EoM:
\[ \phi'' + 2H\phi' = \frac{1}{2\omega + 3} \left\{ 8\pi G_0 a^2 (\rho - 3p) - \phi'^2 \frac{d\omega}{d\phi} \right\} \]

\[ H \equiv \frac{a'}{a} : \text{Hubble parameter} \]

\[ (T^\mu_\nu) = \begin{pmatrix} -\rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix} : \text{Energy-momentum tensor} \]
Gravitational constant

The effective gravitational constant, measured by “Cavendish-type” experiments:

\[ G(\phi) = \frac{G_0}{\phi} \frac{2\omega(\phi) + 4}{2\omega(\phi) + 3} \propto \frac{1}{\phi} \]

To satisfy \( G(\phi_0) = G_0 \)

(Using \( 2\omega(\phi) + 3 = \left\{ \alpha_0^2 - \beta \ln(\phi/\phi_0) \right\}^{-1} \))

The present value of the scalar field:

\[ \phi_0 = \frac{2\omega_0 + 4}{2\omega_0 + 3} = 1 + \alpha_0^2 \]

➢ The present deviation from the GR

Damour and Esposito-Farèse (1996)

- **Time variation of the scalar field**

\[
\phi'' + \left[ 2H \phi' + \frac{1}{2\omega + 3} \phi'^2 \frac{d\omega}{d\phi} \right] = \frac{1}{2\omega + 3} \left[ 8\pi G_0 a^2 (\rho - 3p) \right]
\]

- Friction term

- RD \((p_r = \rho_r/3)\) : \(= 0\)
- MD \((p_m \approx 0)\) : \(\neq 0\)

At present,

\[
\phi_0 = \frac{2\omega_0 + 4}{2\omega_0 + 3} = 1 + \alpha_0^2
\]
Contents

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The locations of the acoustic peaks

\[ H^2 = \frac{8\pi G_0}{3\phi} \rho a^2 - H \frac{\phi'}{\phi} + \frac{\omega}{6} \left( \frac{\phi'}{\phi} \right)^2 \quad (\frac{\phi'}{\phi} \ll H) \]

- "H" is larger than its value under the GR in the early epoch.
- Hence a smaller horizon length at given redshift.
Damping

- The peak scales ($\propto H^{-1}$), the damping scale ($\propto \sqrt{H^{-1}}$).
- Two scales become closer as “$H$” becomes larger.
- Hence the small scale peaks get stronger damping effect.

Suppressing the small scale peaks
Method

Codes:
- **CLASS** (class-code.net)
  To compute the fluctuations in the CMB.
- **Monte Python** (montepython.net)
  To analyze data by using the Markov Chain Monte Carlo method. (MCMC method)

Prior:
- In addition to the \(\Lambda\)CDM model parameters,
  \[ \alpha_0 \in (0, 0.5), \quad \beta \in (0, 0.4) \]

Data:
- **Planck 2015**
  Temperature and polarization anisotropies (\(TT, EE\)),
  their cross-power spectrum (\(EE\)),
  the lensing potential power spectrum.

Result

Scalar-tensor coupling parameters:

\[ \alpha_0^2 < 2.5 \times 10^{-4} - 4.5 \beta \]  (95.45%)  (dashed black)
\[ \alpha_0^2 < 6.3 \times 10^{-4} - 4.5 \beta \]  (99.99%)

Using  \[ 2\omega(\phi) + 3 = \left\{ \alpha_0^2 - \beta \ln(\phi/\phi_0) \right\}^{-1} \]

\[ \omega > 2000 \]  (95.45%),  \[ \omega > 1100 \]  (99%)
\[ \omega > 790 \]  (99.99%)

Previous works:

- **WMAP**  ➢  Nagata *et al.* (2004)  \[ \omega > 1000 \]  (50) at 2\(\sigma\) (4\(\sigma\))
- **Planck 2013**  ➢  Avilez and Skordis (2014)  \[ \omega > 890 \]  at 99%
- **Solar System**  ➢  Bertotti *et al.* (2003), Will (2014)  \[ \omega > 43000 \]  at 2\(\sigma\) (gray line)

\[ \ln \beta > 0.3 \] , our constraint is stronger than that determined in the Solar system study.
Result

Time variation of the gravitational constant:

At the recombination epoch: \( G_{\text{rec}} \equiv G(\phi_{\text{rec}}) \)

\[
\frac{G_{\text{rec}}}{G_0} < 1.0056 \ (95.45\%)
\]

\[
\frac{G_{\text{rec}}}{G_0} < 1.0115 \ (99.99\%)
\]

The deviation from \( G_0 \): < 1.15%

Previous works:

- **WMAP** ➢ Nagata *et al.* (2004) \( G_{\text{rec}}/G_0 < 1.23 \) at \( 4\sigma \) \(< 23\%\)
- **Planck 2013** ➢ Li *et al.* (2013) \( G_{\text{rec}}/G_0 < 1.029 \) at \( 1\sigma \) \(< 2.9\%\)

➢ Our study places the strongest constraint on the deviation of the gravitational constant.
Result: including spatial curvature

- It also changes the acoustic peak scales of the CMB (but not the damping scale)

Prior:

\[ \Omega_K \in (-0.5, 0.5) \]

Nonflat universe case:

\[
\frac{G_{\text{rec}}}{G_0} < 1.0062 \ (95.45\%)
\]

\[
\frac{G_{\text{rec}}}{G_0} < 1.0125 \ (99.99\%)
\]

Flat universe case (same as previous slide):

\[
\frac{G_{\text{rec}}}{G_0} < 1.0056 \ (95.45\%)
\]

\[
\frac{G_{\text{rec}}}{G_0} < 1.0115 \ (99.99\%)
\]

We have found that these constraints are fairly robust against the inclusion of spatial curvature.
Planck vs. WMAP

The difference from the GR mainly arises in the high-\(\ell\) region.

Therefore the constraints from the Planck data are much stronger than those from the WMAP data.

Also the precise polarization spectra contribute to our result.
Summary  
Ooba *et al.* (2016), Phys. Rev. D 93, 122002

- We have constrained scalar-tensor $\Lambda$CDM model from the Planck data by using MCMC method.

- Our results are as follows.
  \[
  \omega > 2000 \ (95.45\%) \quad G_{\text{rec}}/G_0 < 1.0056 \ (95.45\%)
  \]
  \[
  \omega > 790 \ (99.99\%) \quad G_{\text{rec}}/G_0 < 1.0115 \ (99.99\%)
  \]

- The significant improvement of these constraints is attributed to the precise measurements of the diffusion damping effect in the CMB power spectra.
Backup

Brans-Dicke vs This work

Graphs showing the relationship between $\phi$ and $1 + z$ for different values of $\alpha_0$ and $\beta$. The graphs compare Brans-Dicke theory to the work in question.

CosPa2016 @ the University of Sydney

Backup

Brans-Dicke

This work

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